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Neural network-based target tracking control of underactuated autonomous underwater vehicles with a prescribed performance

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ABSTRACT

In this paper, the target tracking control problem is addressed for underactuated autonomous underwater vehicles (AUV) with a prescribed performance. For this purpose, the range and bearing angles of the AUV relative to an underwater target are transformed to a second-order open-loop error dynamic model by using the prescribed performance bound technique. Then, a new tracking controller is proposed such that the tracking errors converge to an arbitrary small ultimate bound and their transient performance are guaranteed with a pre-specified maximum overshoot and the convergence rate. To overcome unmodeled dynamics and external disturbances that are imposed on the vehicle by the wind, waves, and ocean currents, a multi-layer neural network and an adaptive robust controller are adopted. A Lyapunov stability synthesis shows that all signals of the control system are bounded, and tracking errors converge to a small region containing the origin with a prescribed performance. Finally, simulations are performed in MATLAB software and a comparative study verifies the theoretical results.

1. Introduction

The motion control problem of autonomous underactuated underwater vehicles (AUVs) has been a topic of interest over past few decades. Some typical applications of AUVs include rescue, search, surveillance, reconnaissance, mine counter-measures, inspection, identification, oceanography, and so on. In contrast to fully-actuated underwater vehicles, the underactuated ones possess less actuators than the degrees of freedom. Accordingly, the tracking control problem of these vehicles is more difficult and more complex than that of the fully-actuated ones. This limitation is due to the intentional decrease of the independent actuators to lessen the cost and maintenance of the system (Shojaei and Dolatshahi, 2017). Motivated by the vast applications and the challenging nature of underactuated AUVs, most of researchers have proposed valuable methods for the motion control of underactuated ocean vehicles. Reference (Shojaei and Dolatshahi, 2017) has developed a robust dynamic surface control for underactuated underwater vehicles. In (Shojaei, 2017), a novel trajectory tracking controller is introduced under thesaturation constraint. In (Do et al., 2004) and (Do, 2015), the robust controllers are designed based on the backstepping method. A cooperative line-of-sight target tracking is proposed in (Glotzbach et al., 2015). Reference (Shojaei and Arefi, 2015) has proposed a neural adaptive feedback control for underactuated underwater vehicles to deal with the uncertain parameters. Since stochastic obstacles may appear in the desired trajectory, some collision avoidance control algorithms are proposed in (Li and Wang, 2013; Lin et al., 2017; Ataei and Yousefi-Koma, 2015; Conti et al., 2015). To cope with unknown parameters, model-based adaptive controllers are developed in (Sarhadi et al., 2016a, 2016b; Hassanein et al., 2016). To deal with unstructured uncertainties, the sliding mode-based controllers are proposed in (Xu et al., 2015; Esfahani et al., 2015; Cui et al., 2016; Elmokadem et al., 2017; Gao et al., 2017; Bessa et al., 2010). In (Miao et al., 2017), a spatial curvilinear path-following controller has been proposed for underactuated AUVs by using the backstepping technique and the active disturbance rejection control. Reference (Peymani and Fossen, 2015) has proposed a novel path-following controller for AUVs by employing the Lagrange multiplier method to satisfy pre-specified constraints. Moreover, the leader-follower formation controllers are designed in (Shojaei, 2016a; Cui et al., 2010; Park, 2015) for the cooperation of multiple AUVs. Recently, some novel controllers have been proposed in the literature to address the motion control of AUVs (Yan and Yu, 2018; Li et al., 2018; Karkoub et al., 2017). From a review of the previous works (Shojaei and Dolatshahi, 2017; Shojaei, 2016a, 2017; Do et al., 2004; Do, 2015; Glotzbach et al., 2015; Shojaei and Arefi, 2015; Li and Wang, 2013; Lin et al., 2017; Ataei and Yousefi-Koma, 2015; Conti et al., 2015; Sarhadi et al., 2016a, 2016b; Hassanein et al., 2016; Xu et al., 2015; Esfahani et al., 2015; Cui et al., 2010, 2016; Elmokadem et al., 2017; Gao et al., 2017; Bessa et al., 2010; Miao et al.,

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2017; Peymani and Fossen, 2015; Park, 2015; Yan and Yu, 2018; Li et al., 2018; Karkoub et al., 2017), it turns out that the previous controllers cannot ensure the *prescribed* transient and steady-state performances of the tracking errors. In other words, the transient and steady-state responses specifications such as the convergence rate, maximum overshoot/undershoot and final tracking accuracy cannot be specified before the beginning of the tracking mission in previous controllers.

In the design of tracking controllers, the stability problem of underactuated autonomous underwater vehicles under structured and unstructured uncertainties is a challenging problem. Besides, the conventional nonlinear controllers are not able to guarantee the stability of these systems with a prescribed performance. In certain cases, the adjustment of the transient response parameters such as overshoot and convergence rate are essential factors to design nonlinear controllers, and the most of the classical nonlinear controllers are not able to guarantee the stability with a prescribed performance. Furthermore, AUVs are highly nonlinear, and in practice, structured and unstructured uncertainties cannot be ignored since their effects cause the instability in the control system. As a result, the underactuated autonomous underwater vehicles have to be controlled by methods that compensate model uncertainties such as the robust and adaptive controllers. In such techniques, it is difficult to obtain a desirable transient response because of the parameters estimation and rough control signals that are produced by the robust controller. Consequently, the stability guarantee for underactuated AUVs with a prescribed performance still remains a challenging open problem. Toward this end, an approximation-free trajectory tracking controller is proposed in (Bechlioulis et al., 2017) for underactuated AUVs with the prescribed performance technique which is originally introduced for feedback linearizable MIMO nonlinear systems in (Bechlioulis and Rovithakis, 2008) and its successful applications are available in the literature (Wang et al., 2017; Bechlioulis et al., 2014; Bechlioulis and Rovithakis, 2014). However, the reference (Bechlioulis et al., 2017) ignores the advantages of approximation-based methods such as neural network and adaptive techniques which are the main topic of this paper. It should be noted that the approximation-based methods including a combination of neural networks and adaptive robust techniques provide a powerful solution to compensate for the different types of uncertainties including unknown parameters, unmodeled dynamics, measurement noise, and time-varying external disturbances in practice. In contrast to (Bechlioulis et al., 2017), our proposed neural network adaptive robust controller is capable to learn every level of uncertainties by the online adaptation. Therefore, the proposed controller maintains its robust performance with increasing the level of uncertainties and the amplitude of external disturbances at the expense of more control activities. Moreover, compared with (Bechlioulis et al., 2017), our proposed controller not only restricts the time evolution of the tracking errors within prescribed performance bounds but also it improves the final tracking accuracy within these bounds by using the neural adaptive robust method.

According to the above literature review, the neural adaptive tracking control of uncertain underactuated AUVs with a guaranteed prescribed performance has not been addressed sufficiently in the literature (Shojaei and Dolatshahi, 2017; Shojaei, 2016a, 2017; Do et al., 2004; Do, 2015; Glotzbach et al., 2015; Shojaei and Arefi, 2015; Li and Wang, 2013; Lin et al., 2017; Ataei and Yousefi-Koma, 2015; Conti et al., 2015; Sarhadi et al., 2016a, 2016b; Hassanein et al., 2016; Xu et al., 2015; Esfahani et al., 2015; Cui et al., 2010, 2016; Elmokadem et al., 2017; Gao et al., 2017; Bessa et al., 2010; Miao et al., 2017; Peymani and Fossen, 2015; Park, 2015; Yan and Yu, 2018; Li et al., 2018; Karkoub et al., 2017; Bechlioulis et al., 2017). Compared with all of previously proposed controllers (Shojaei and Dolatshahi, 2017; Shojaei, 2016a, 2017; Do et al., 2004; Do, 2015; Glotzbach et al., 2015; Shojaei and Arefi, 2015; Li and Wang, 2013; Lin et al., 2017; Ataei and Yousefi-Koma, 2015; Conti et al., 2015; Sarhadi et al., 2016a, 2016b; Hassanein et al., 2016; Xu et al., 2015; Esfahani et al., 2015; Cui et al., 2010, 2016; Elmokadem et al., 2017; Gao et al., 2017; Bessa et al., 2010; Miao et al., 2017; Peymani and Fossen, 2015; Park, 2015; Yan and Yu, 2018; Li et al., 2018; Karkoub et al., 2017; Bechlioulis et al., 2017) for autonomous AUVs, this paper proposes a neural adaptive robust controller to achieve the tracking of a desired target in the presence of unmodeled dynamics, unknown parameters, and environmental disturbances which are induced by waves, ocean currents, and high pressure water by the prescribed performance technique. To obtain the control objectives, a second-order open-loop error dynamic model is developed under a nonlinear transformation. Next, the controller is proposed by using a filtered tracking error. A multi-layer neural network and an adaptive robust controller are simultaneously employed to compensate both structured and unstructured uncertainties. As a result, the proposed controller guarantees the robust stability with a prescribed performance against unmodeled dynamics and external disturbances. Hence, the main contributions of this paper is summarized as follows:

A target tracking controller is proposed for underactuated AUVs in three-dimensional space with the prescribed transient and steady-state performance. By employing a nonlinear transformation, a new second-order Euler-Lagrange formulation of AUVs is developed in terms of prescribed performance errors for the first time which preserves all properties of AUV dynamics. Then, a robust tracking controller is designed without any singularity by an effective combination of multi-layer neural networks and an adaptive robust controller which compensate all types of model uncertainties.

The rest of this paper is organized as follows. In the next section, the problem formulation is presented. In Section 3, the controller design and its Lyapunov stability analysis are stated. In Section 4, simulation results are given and conclusions are drawn in Section 5.

2. Problem statement

2.1. Notations

The following notations are used in this paper. the term $\|x\| = \sqrt{x^T x}$ denotes the Euclidean norm of an arbitrary vector $x \in \Re^n$, for an arbitrary matrix A the Frobenius norm is given by $\|A\|_f^2 = tr\{A^T A\}$ or the induced norm $\|A\|^2 = \lambda_{\max}(A^T A)$ where $tr\{\bullet\}$ denotes the trace operator, $\lambda_{\min}(\bullet)$ ($\lambda_{\max}(\bullet)$) denotes the smallest (largest) eigenvalue of a matrix, and $\Re^+$ denotes the set of real positive numbers.

2.2. AUV kinematics and dynamics

This section presents the AUV motion equations. Fig. 1 shows the three-dimensional coordinates of AUV with body-fixed and earth-fixed frames. It is assumed that the origin of the body-fixed frame is located in the vehicle center of mass. The kinematic and dynamic equations of a 5-DOF underactuated AUV are stated as follows (Do and Pan, 2009; Fossen, 2002):

$$\begin{aligned}
\dot{x} &= u\cos(\psi)\cos(\theta) - v\sin(\psi) + w\sin(\theta)\cos(\psi),\\
\dot{y} &= u\sin(\psi)\cos(\theta) + v\cos(\psi) + w\sin(\theta)\sin(\psi),\\
\dot{z} &= -u\sin(\theta) + w\cos(\theta),\\
\dot{\theta} &= q,\\
\dot{\psi} &= r/\cos(\theta),
\end{aligned} \tag{1}$$

$$\begin{aligned}
m_{11}\dot{u} &= m_{22}vr - m_{33}wq - d_{11}u - f_u(u) + \tau_u - \tau_{wu}(t),\\
m_{22}\dot{v} &= -m_{11}ur - d_{22}v - f_v(v) - \tau_{wv}(t),\\
m_{33}\dot{w} &= m_{11}uq - d_{33}w - f_w(w) - \tau_{ww}(t),\\
m_{55}\dot{q} &= (m_{33} - m_{11})uw - d_{55}q - f_q(q) - \rho g\nabla GM_L\sin(\theta) + \tau_q - \tau_{wq}(t),\\
m_{66}\dot{r} &= (m_{11} - m_{22})uv - d_{66}r - f_r(r) + \tau_r - \tau_{wr}(t),
\end{aligned} \tag{2}$$

where x, y, z, θ, and ψ denote the position and orientation of the